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FULL LENGTH ARTICLE

Multivariate geochemical and statistical methods applied to assessment of organic matter potentiality and its correlation with hydrocarbon maturity parameters (Case study: Safir-1x well, North Western Desert, Egypt)

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Abstract The TOC-Rock–Eval pyrolysis and vitrinite reflectance measurements for "15" shale rock samples, as well as, multivariate statistical analysis are discussed to investigate hydrocarbon, source rock characteristics, correlation between the assessed parameters (S1, S2, HI, S1 + S2, QI, BI, PI, TOC) and the impact of changes in the T_{max} and R_o% on the assessed parameters in Safir exploratory-1x well in Safir oilfield. The geochemical analysis indicated that the Bahariya Formation is considered to be a poor source rock for oil generation with a low degree of thermal maturation in comparison with the Alam El Bueib and Khatatba Formations. However, Alam El Bueib is found to be a good source rock for oil generation with slightly higher thermal maturation. Interestingly, Khatatba Formation lies within the oil and gas generation window and shows an excellent source rock potential. Based on statistical findings of cluster and factor analysis, the source rocks in the study area are classified into two types corresponding to two different clusters. Cluster I includes Alam El Bueib and characterized by kerogen type II and II/III whereas, cluster II, characterized by kerogen type III, is subdivided into two subgroups (IIa and IIb) and represents Bahariya and Khatatba source rocks. Nonparametric tests (*K*-independent samples) between the dataset of 15 samples confirm that the distribution of values from respective parameters exhibits significant difference ($P < 0.05$) except for PI and BI. On the other hand, the nonparametric tests (2-independent samples) showed that there is no significant difference ($P > 0.05$) in the distribution of HI and QI values indicating that both HI and QI values remain constant with increasing thermal maturity. Unlike TOC and HI, Pearson's and linear regression analysis indicated a significant correlation between TOC and S2. Nevertheless, two different trends were observed between S1 and S2.

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Moreover, the R_o% and T_{max} were found to be positively correlated. Interestingly, our study showed no significant correlation between HI, QI, BI and thermal maturity (R_o% and T_{max}), while, a good correlation between TOC, S2 and thermal maturity was observed.

1. Introduction

The Western Desert of Egypt covers two thirds of the whole area of Egypt and considered as an excellent potential oil and gas rich area of about 700,000 km^2 and is also the second largest hydrocarbon producing part of Egypt, next to the Gulf of Suez. Safir oilfield (Fig. 1) is characterized by high oil and gas accumulations, which represents more than one third of the oil production from the Western Desert of Egypt [1]. Khalda Petroleum Company was the leading producer since the discovery of Safir oilfield in 1986. This field fits a feature of structural culminations of anticlinal forms with NE–SW axial traces [2].

The main sedimentary rocks of the northern Western Desert [3], range in age from Paleozoic to Miocene (Fig. 2). The stratigraphic rock units comprise mainly marine and subordinate fluvial–deltaic sediments, which are composed of clastic, carbonate and argillaceous sediments (Fig. 2). The lower part of the Jurassic is represented by non-marine siliciclastics of the Ras Qattara Formation. This formation includes mostly sandstone with interbedded shales, which rest unconformably on the Paleozoic Nubian sandstone (Fig. 2). The lower Jurassic Ras Qattara Formation also conformably underlies the Middle Jurassic Khatatba Formation (Fig. 2). The Khatatba Formation is composed mainly of shales and sandstones with coal seams, and is overlain conformably by Upper Jurassic Masajid Formation. The shallow-marine carbonates of the Masajid Formation represent the maximum Jurassic transgression, and are overlain unconformably by Cretaceous units (Fig. 2). The Cretaceous units comprise the Alam El-Bueib, Alamein, Kharita and Bahariya Formations. The Alam El-Bueib Formation (Lower Cretaceous) composed of shallow-marine sandstones and carbonates. Alamein Formation represents a carbonate and fine-grained break between two sandstone cycles Alam El Bueib Formation from the base and Kharita Formation at the top. Kharita Formation consists of sandstones intercalated with small amounts of shales, is overlain conformably by Bahariya Formation. The Bahariya Formation (Cenomanian) is a shallow marine and nearshore deposits and overlain by the Abu Roash (G) member and then followed by transgression sediments (predominantly carbonates) of the Abu Roash (F) to (A) members (Fig. 2).

The source rock potential and the hydrocarbon generation of the northern Western Desert of Egypt were studied by many authors; among them, [4–11], Ramadan et al. [12], El Nady [13–15] reveal that the Bahariya and Khatatba source rocks act as a source and reservoirs for oil generation in the Qarun and Misaada oilfields. El Nady [16] reported that Alam El Bueib source rock has organic matter characteristics of deposition in clay-rich deltaic environment with significant input of terrestrial organic matter. Ramadan et al. [17] showed that Khatatba Formation bears a mature source rock, and has poor to good generating capability for both oil and gas. Masajid and Alam El Bueib formations bear mature source rocks and have poor to fair generating capability for generating gas (type III kerogen).

This study was aiming to discuss the source rock characteristics and the hydrocarbon generation of Safir oilfield. In addition, we investigated the impact of changes in the T_{max} and R_o% on the assessed parameters (S1, S2, S1 + S2, HI, QI,

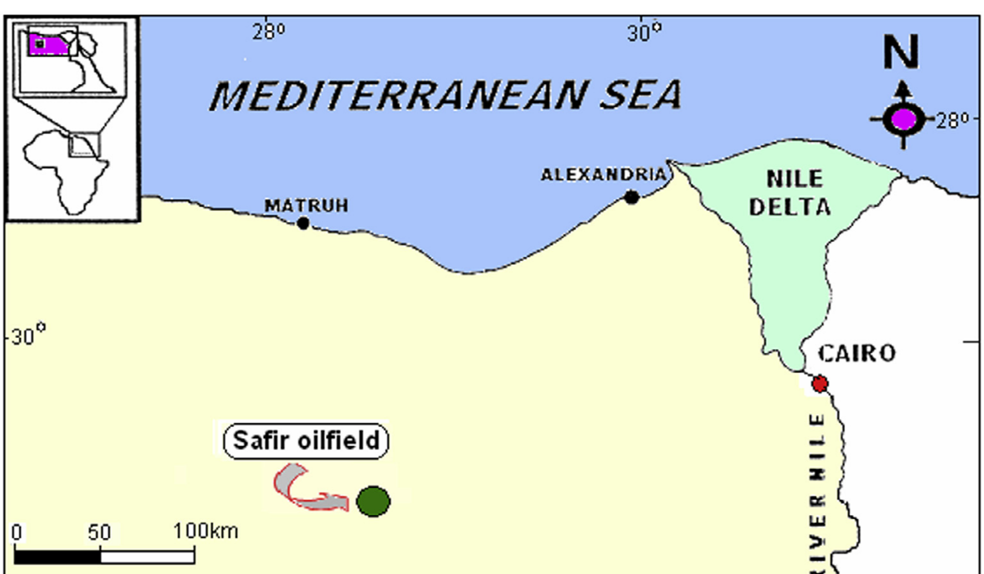

Figure 1 Location map of the studied Safir oilfield, North Western Desert, Egypt.

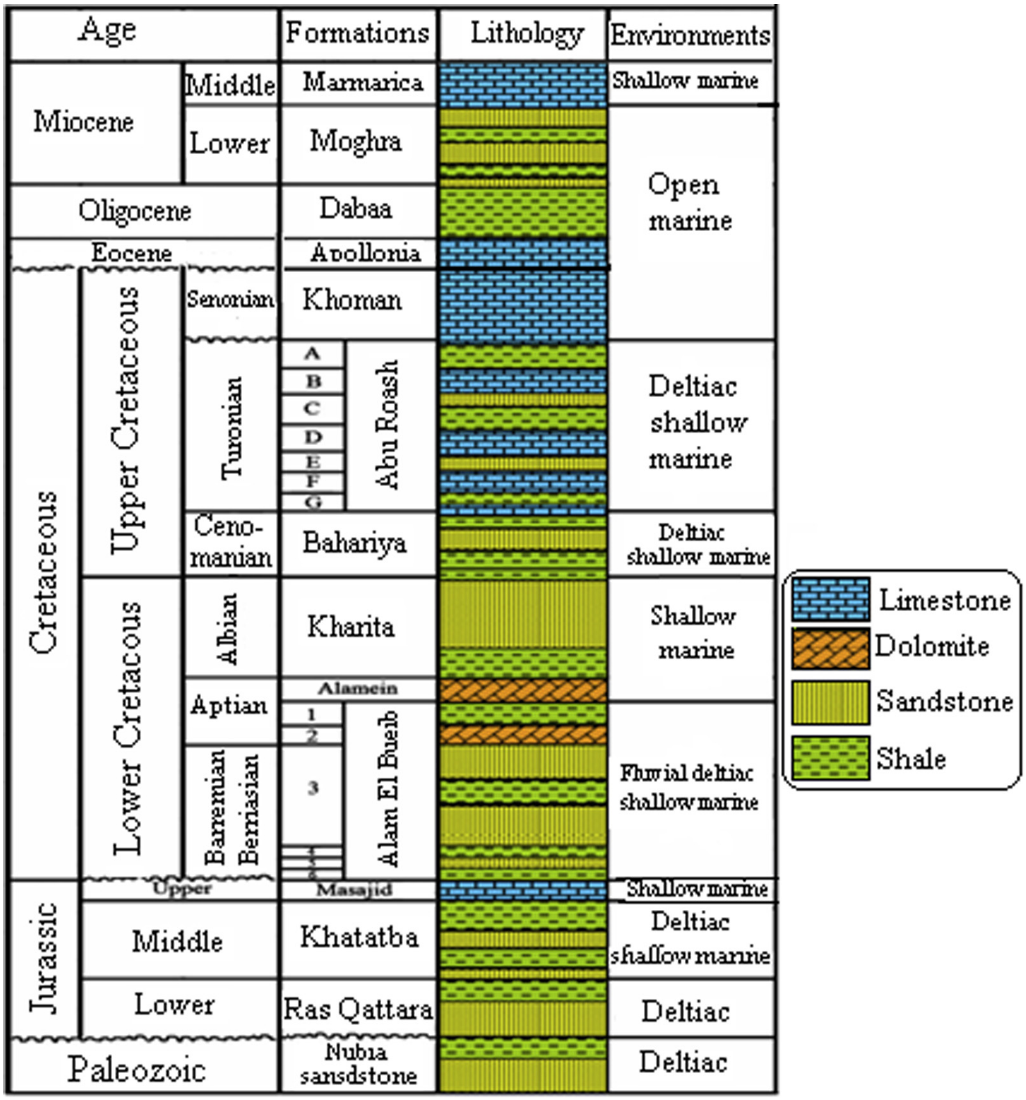

Figure 2 Generalized stratigraphic column of North Western Desert [3].

BI, PI, TOC) of petroleum potential of organic materials. To these points, Rock–Eval pyrolysis analysis, vitrinite reflectance measurements and burial history modeling in exploratory Safir-1x well were performed to evaluate the source rock potentials and the degree of thermal maturation of the succession including Bahariya, Alam El Bueib and Khatatba Formations and to explore the relationship between the petroleum potential and maturity for the studied samples. In order to get the correlation between the aforementioned parameters and to specify the type of source rock, multivariate statistical analysis was performed.

2. Samples and methods

Fifteen selected shale rock ditch samples from Bahariya, Alam El Bueib and Khatatba Formations of Safir-1x well (Table 1) were analyzed for total organic carbon, and Rock–Eval pyrolysis measurements. The TOC content and Rock–Eval pyrolysis analyses were made in the laboratories of the Egyptian Petroleum Research Institute [18], which were performed on 100 mg crushed whole rock samples, heated to 600 °C in a helium atmosphere, using a Rock–Eval II unit with a total organic carbon module. The characters of source rocks were incorporated into basin modeling to reconstruct the burial history of the basin and to estimate the timing of hydrocarbon generation and expulsion of the source rocks.

Multivariate statistical analysis was applied to evaluate the source rock potentiality and clarify the relationship between petroleum potential and maturity. The results obtained for studied samples were statistically analyzed using cluster analysis (hierarchical and *K*-means cluster analysis), Factor analysis, *K*-independence and 2-independence sample *T*-tests, linear regression and Pearson's correlation by SPSS 15.0 [19] and GraphPad prism version 5.01 for windows (GraphPad Software, San Diego, California, USA).

2.1. Cluster analysis

Cluster analysis is based on a matrix measuring the differences between each parameter of each sample. Two basic types of cluster analyses are known: *K*-Means and hierarchical types. For *K*-means analysis, it is necessary to define the number of

Table 1 TOC-Rock–Eval pyrolysis and vitrinite reflectance data of the shale rock samples from Safir-1x well, North Western Desert, Egypt.

Formations	Depth, m	TOC	S1	S2	HI	OI	T_{max}	PI	R_o%	QI	BI	GP
Bahariya	2489	0.44	0.05	0.89	202	129	425	0.02	0.2	2.13	0.11	0.94
Bahariya	2500	0.64	0.17	0.91	142	144	428	0.02	0.45	1.68	0.26	1.08
Bahariya	2520	0.84	0.12	1.32	157	101	428	0.04	0.55	1.71	0.14	1.44
Bahariya	2550	0.91	0.17	1.48	163	132	430	0.03	0.55	1.81	0.18	1.65
Bahariya	2580	0.98	0.49	1.88	192	113	425	0.21	0.56	2.41	0.5	2.37
Alam El Bueib	2600	1.15	1.9	5.04	438	117	436	0.27	0.51	6.03	1.65	6.94
Alam El Bueib	2620	1.54	0.95	5.03	326	146	438	0.16	0.61	3.88	0.61	5.98
Alam El Bueib	2640	1.89	0.96	5.15	272	189	440	0.16	0.62	3.23	0.5	6.11
Alam El Bueib	2700	2.18	1.04	5.67	260	208	437	0.15	0.65	3.07	0.47	6.71
Alam El Bueib	2720	2.4	2.00	5.87	373	198	440	0.19	0.66	3.27	0.83	7.87
Khatatba	2740	3.71	1.11	5.81	157	183	437	0.16	0.68	1.86	0.29	6.92
Khatatba	2760	3.6	1.1	5.74	160	189	435	0.16	0.62	1.9	0.3	6.84
Khatatba	2780	3.68	1.88	6.11	166	180	458	0.46	0.71	2.17	0.51	7.99
Khatatba	2800	4.01	1.78	7.45	186	199	441	0.19	1.1	2.3	0.44	9.23
Khatatba	3100	4.2	2.37	8.38	152	149	455	0.22	1.12	2.55	0.56	10.75

S1: mgHC/g rock; S2: mgCO2/g rock; HI (hydrogen index): mgHC/g TOC; OI (oxygen index): mgCO2/g TOC; PI (Production index) S1/(S1 + S2); QI (Quality index) (S1 + S2)/TOC; BI (Bitumen index) S1/TOC; GP (Generating potential) S1 + S2.

groups into which the samples/parameters are to be classified, while hierarchical cluster analysis enables the grouping of the samples or parameters without any previous classification. These differences are squared. By adding the individual matrices, a summed matrix is obtained. In the case when the values of the parameters are essentially different, they should preliminarily be standardized, in order that in the final matrix each parameter becomes an equal share. Based on the final matrix, a dendrogram is constructed, which involves all samples or parameters being classified into groups on the basis of all data taken into consideration [20].

2.2. Factor analysis

Factor analysis is a statistical method used for combining a large number of data into a considerably smaller number of factors, representing groups of initially mutually linearly dependent parameters containing the same amount of information as their constituent parameters [21]. The values of the coefficients preceding the parameters, marked as loadings, define the significance of a particular parameter in the characterization of an analyzed group of samples. The significance of a particular factor is defined by its characteristic value and percent of variance [22,23]. In order to determine the relationship between the parameters for the sake of classification of the samples, an interdependence diagram of two factors may be constructed [24]. In the case when the parameters are defining factors reflecting certain types of reaction characteristic for the investigated group of samples, the course of these processes and their mutual agreement can be proven by constructing corresponding correlation diagrams of these factors [24].

2.3. Non parametric test analysis

2.3.1. K-Independence sample test

$$\chi^2 = \sum_{i=1}^{2}\sum_{j=1}^{k}\frac{(O_{i,j} - E_{i,j})^2}{E_{i,j}}$$

where $O_{i,j}$ represents observation number, i is number of row, j is number of column, and $E_{i,j}$ represents expectation number, i is number of row, j is number of column. If P (probability) $> \alpha$ (0.05, significance level), accept null hypothesis (H_0).

2.3.2. Independent T-test

The 2-independent T-tests used here evaluate the probability that the mean value of a particular parameter is exhibited by two data sets and obtained by using the following equation

$$S_p^2 = \frac{(n-1)S_1^2 + (n_2-1)S_2^2}{n_1 + n_2 - 1}$$

where n_1, n_2 represent the number of measurements and S_1, S_2 represent the standard deviation. If P (probability) $> \alpha$ (0.05, significance level), accept null hypothesis (H_0). Chi-squared (χ^2) statistics were used to assess the normality of the distribution of values in the data set for a particular parameter.

$$\chi^2 = \sum_{i=1}^{r}\frac{(n_i - e_j)^2}{e_i}$$

where r is the number of categories, n_i are the observed frequencies and e_i are the theoretical frequencies.

2.4. Pearson's correlation coefficient

Pearson's correlation coefficient is a statistical measure of the strength of a linear relationship between paired data. The correlation coefficient can range from −1 to +1, with −1 indicating a perfect negative correlation, +1 indicating a perfect positive correlation, and 0 indicating no correlation at all. (A variable correlated with it will always have a correlation coefficient of 1.)

2.3. Linear regression

Linear regression is the next step after correlation. It is used when we want to predict the value of a variable based on the value of another variable. The variable we want to predict is called the dependent variable (or sometimes, the outcome variable). The variable we are using to predict the other variable's value is called the independent variable (or sometimes, the predictor variable).

3. Results and discussions

3.1. Geochemical methods

Source rock characterization was investigated for the purpose of organic carbon richness, types of organic matter and thermal maturity level, as well as, the capability of generation of thermally mature oil and gas accumulations buried in sedimentary succession [25,26].

3.1.1. Organic carbon richness

Based on classification proposed by Peters [26] the organic content of Bahariya Formation samples varies from poor to fair with TOC values ranging from 0.44 to 0.98 wt%. The generating source potential "S1" and "S2" values ranging from 0.05 to 0.49 and 0.89 to 1.88 mg/g, respectively (Table 1) indicate poor to fair generating capability. The productivity index (S1/S1 + S2) of these rocks is generally less than unity ranging from 0.05 to 0.21 (Table 1) indicating the shale rocks of Bahariya Formation have a medium to high source rock generating potential. The shale section of Alam El Bueib Formation containing TOC varies from 1.15 to 2.40 wt% (Table 1) indicating a good source rock. The pyrolysis-derived "S1" and "S2" values of Alam El Bueib Formation samples range from 0.95 to 2.00 mg/g and 5.03 to 5.87 mg/g, respectively (Table 1) indicating good generating potential. These samples have high production index (PI) of 0.15–0.27 (Table 1) indicating the shale rocks of the Alam El Bueib Formation have a good source rock generating potential. The organic content (TOC) of the Khatatba Formation ranges between 3.60 and 4.20 wt% (Table 1) indicating an excellent source rock [25]. The pyrolysis derived S1 and S2 values of Khatatba Formation samples have wide range, from 1.10 to 2.37 mg/g and 5.74 to 8.38 mg/g, respectively (Table 1). These values indicate a highly variable source rock potential from good to very good. The productivity index (S1/S1 + S2) of these rocks ranges from 0.16 to 0.46 (Table 1) indicating the shale rocks of Khatatba Formation have a high source rock potential.

3.2. Types of organic matter

The type of organic matter (kerogen) is considered the second most important parameter in evaluating the source rock. Present-day kerogen type was characterized based on Rock–Eval pyrolysis data, such as hydrogen index (HI) and oxygen index (OI) data (Table 1). The kerogen type is defined by the plotting of hydrogen index (HI) vs. oxygen index (OI) on a Van Krevelen diagram for the studied source rocks (Fig. 3). Based on these plots, the samples from shale source rock intervals of Bahariya, Alam El-Bueib and Khatatba Formations from Safir-1x well, reflect that Bahariya, Alam El-Bueib and Khatatba shales contain mixed kerogen types II–III. These kerogen types are derived from land plants and preserved remains of algae [25]. Mixed kerogen type characterizes mixed environment containing admixture of continental and marginal marine organic matter and has the ability to generate oil and gas accumulations [27].

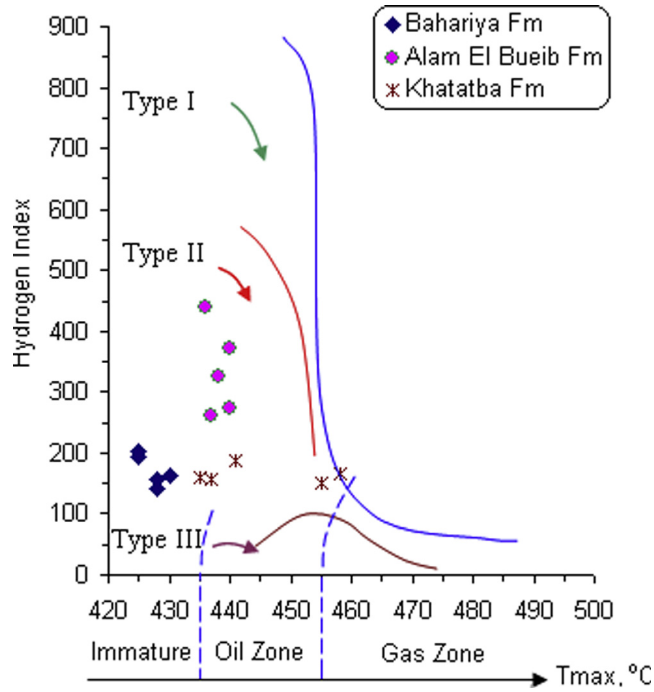

Figure 3 Hydrogen index (HI) vs. T_{max} showing the organic matter types and maturity of the studied source rocks, Safir-1x well, North Western Desert, Egypt [18].

3.3. Thermal maturity

The most common method used for determining the stage of maturation is the vitrinite reflectance measurement (R_o%), and pyrolysis T_{max} where it is considered one of the most useful indicators for organic matter maturation [28–30]. The data of vitrinite reflectance measurements (R_o%) were also used to indicate the phases of hydrocarbon generation.

The pyrolysis T_{max} of Bahariya Formation ranged from 425 to 430 °C and vitrinite reflectance measurements (R_o%) ranged from 0.20% to 0.56% (Table 1) reflecting immature source rocks. The Alam El Bueib and Khatatba source rocks have T_{max} values ranging from 436 to 440 °C, R_o% from 0.51% to 0.66% and from 435 to 455 °C and R_o% from 0.62 to 1.12, respectively (Table 1) indicating mature source rocks and have capability of oil generation.

To assess the maturity and Kerogen type, the obtained data of the studied samples were plotted on a HI vs. T_{max} diagram [18] (Fig. 3). The hydrogen index (HI) with maximum temperature (T_{max}) values of the studied shale source rocks of the Bahariya, Alam El Bueib and Khatatba Formations ranges from 142 to 202 mgHC/gTOC, 260 to 430 and 152 to 186, respectively and T_{max} ranges from 425 to 340 °C, 436 to 440 and 435 to 458, respectively (Table 1) indicating that the Bahariya Formation is an immature source rock and considered as a poor source for oil generation, having a lesser degree of thermal maturation in comparison with Khatatba and Alam El Bueib formations. Alam El Bueib and shale source rocks of Khatatba Formations are located within the oil generation and considered excellent source rock potential (Fig. 3).

The maturity level can also be expressed by production index (PI), which is defined as the ratio of the amount of hydrocarbons generated in the total amount of the organic matter. The PI value less than 0.05 indicates an immature source rock that has generated little or no petroleum. PI from 0.05 to 0.40 is within the oil window, while PI increases up to 0.50 when the petroleum generative capacity of the kerogen has been spent. The studied source rocks have PI values in the range of 0.02–0.04 (Table 1) for the Bahariya Formation indicating an immature source rock that has generated little or no petroleum. The Alam El Bueib and Khatatba source rocks have production index (PI) ranging from 0.15 to 0.27 and 0.16 to 0.46, respectively (Table 1) indicating that most of the source rocks are thermally mature and within the oil window.

3.4. Statistical methods

The multivariate statistical analysis is the construction of cluster analysis (hierarchical and *K*-means cluster analysis), Factor analysis, *K*-independence and 2-independence sample *T*-tests, linear regression and Pearson's correlation.

3.4.1. Cluster analysis

The set of 10 source parameters (R_o%, T_{max}, HI, QI, BI, PI, S1, S2, TOC, S1 + S2) were subjected to hierarchical cluster analysis using the word method, which was proven to be the most reliable according to the up-to-date organic geochemical investigations. Based on the different HI values, the samples were distinguished into two main clusters: the first one (cluster I) of high HI values ($\geqslant$200 mg/g) and the second (cluster II) of HI values lower than 200 mg/g. However, the samples of cluster II of comparable HI values have showed variability in other parameters like TOC, S1, S2, T_{max} and R_o. To this point, cluster II was further subgrouped into cluster IIa and IIb [21]. The resulting dendrogram (Fig. 4) showed two types of clusters which reflect two types of source rocks. Cluster I that represents Alam El Bueib source rock is found to be a good source rock for oil generation with slightly higher thermal maturation and characterized by HI ranging from 260 to 438 mgHC/gTOC reflecting that these source rocks were characterized by kerogen type II and II/III. Cluster II indicates two separate subgroups IIa and IIb. Cluster IIa represents Bahariya Formation which is characterized by HI ranging from 142 to 202 mgHC/gTOC reflecting kerogen type III. However, cluster IIb represents Khatatba Formation characterized by HI ranging from 152 to 186 mgHC/gTOC reflecting kerogen type III. By applying *K*-means cluster analysis on the same set of source parameters, the results showed that all samples belong to cluster II except for three samples (6, 7, 10) which belong to cluster I (Table 2).

Table 2 *K*-means cluster analysis of assessed parameters of petroleum potential of organic materials.

Sample number	Formations	Cluster	Distance
1	Bahariya	2	37.803
2	Bahariya	2	46.059
3	Bahariya	2	65.379
4	Bahariya	2	35.72
5	Bahariya	2	48.886
6	Alam El Bueib	1	69.52
7	Alam El Bueib	1	53.569
8	Alam El Bueib	2	92.76
9	Alam El Bueib	2	90.027
10	Alam El Bueib	1	44.817
11	Khatatba	2	35.86
12	Khatatba	2	38.079
13	Khatatba	2	34.837
14	Khatatba	2	40.014
15	Khatatba	2	39.203

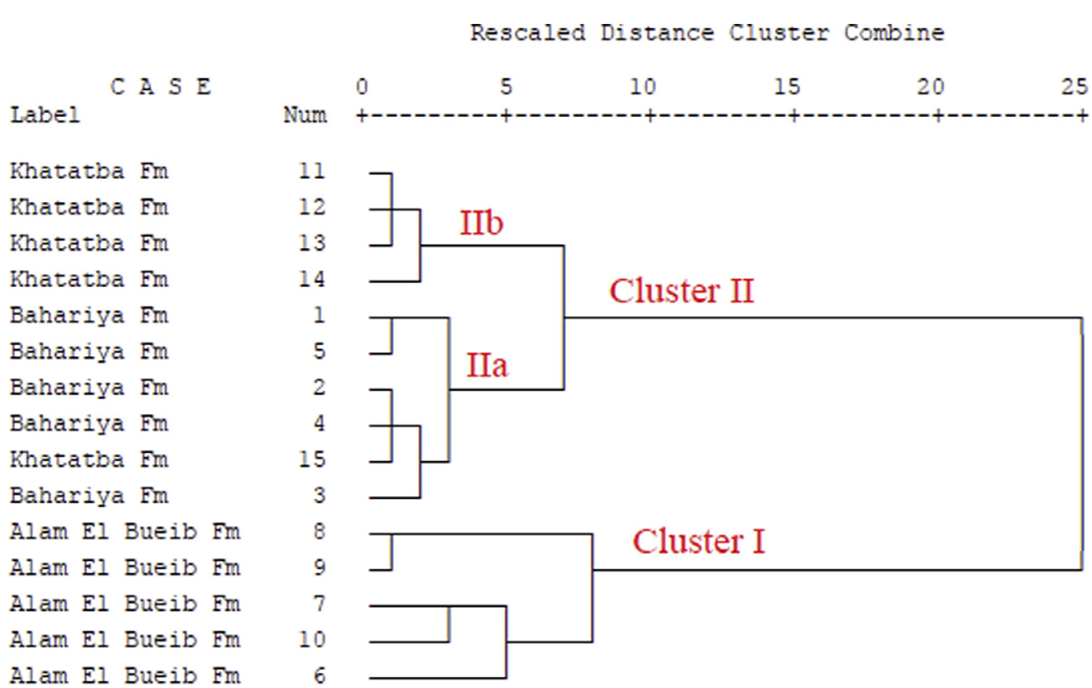

Figure 4 Hierarchical cluster analysis dendrogram using word method.

Table 3 Factor analysis of the measured parameters in the study area.

Variable	Factor 1	Factor 2
TOC%	0.839	−0.498
S1	0.966	0.13
S2	0.972	−0.105
HI	0.275	0.901
OI	0.611	−0.338
T_{max}	0.879	−0.185
R_o%	0.775	−0.385
QI	0.368	0.91
PI	0.779	0.137
BI	0.506	0.831
S1 + S2	0.987	−0.05
Eigen value	6.376	2.924
Of Variance%	57.96	26.58
Cumulative%	57.96	84.54

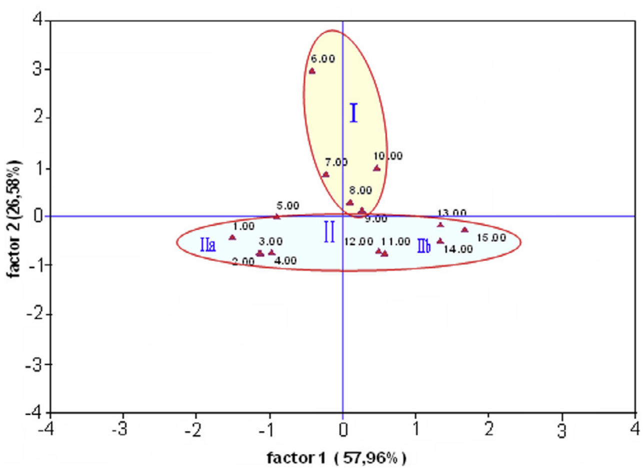

Figure 5 Classification of source rocks in the study area using factor analysis.

3.4.2. Factor analysis

To get a more detailed classification of the source rock potential in the study area, a factor analysis of the source parameters was carried out using principle component analysis (Table 3). According to up-to-date organic geochemical investigations, this method has been shown to be the most convenient [22,31]. Factor analysis showed that there are two factors affecting the source rocks evaluation potentiality in the study area, factor 1 includes (TOC, S1 and S2) which determine the quantity of the organic matter and (R_o%, T_{max} and PI) which determine the thermal maturity of the organic matter. On the other hand, factor 2 includes (HI, QI and BI) which determine the quality of the organic matter. By plotting the ratios of factor1 vs. factor 2 (Fig. 5), two groups of source rocks were observed. Group 1 represented Alam El Bueib samples and Group II was classified into two subgroups: Bahariya and Khatatba samples. By comparing the results obtained by factor and cluster analyses, both methods confirmed the existence of two distinct source rock types.

3.4.3. Nonparametric test analyses

Nonparametric tests (*K*-independent samples) between the dataset of 15 samples confirmed that the distribution of values from respective parameters exhibits significant difference ($P < 0.05$, Table 4) except for PI and BI. Nonparametric tests (2-independent samples) showed that there is no significant difference ($P > 0.05$, Table 5) in the distribution of HI and QI values. The distribution of HI and QI values remains constant with increasing thermal maturity.

3.4.4. Pearson's correlation coefficient and linear regression analyses

To investigate the relation between the assessed parameters (S1, S2, S1 + S2, HI, QI, BI, PI, TOC) of petroleum potentiality and to investigate the impact of changes in the T_{max} and R_o% on these parameters, we applied Pearson's correlation (Table 6) and linear regression analysis. The plot of S2 vs. TOC showed a strong correlation (Fig. 6a), indicating that

Table 4 The nonparametric tests (*K*-independent samples) between the measured parameters for the studied samples.

Tests		Parameters									
		TOC%	S1	S2	HI	T_{max}	R_o%	QI	PI	BI	S1 + S2
(a) Kruskal Wallis test	χ^2	12.5	9.797	11.580	9.472	9.765	9.941	10.220	5.380	8.420	10.820
	Sig.	0.002	0.007	0.003	0.009	0.008	0.007	0.0060	0.068	3.750	10.179
(b) Median	χ^2	10.179	10.179	10.179	10.179	5.000	6.667	8.571	1.66	3.750	10.179
	Sig.	0.006	0.006	0.006	0.006	0.082	0.036	0.014	0.435	0.153	0.006
(c) Jonckheere Terpstra	Sig.	0.00	0.002	0.00	0.832	0.002	0.001	0.492	0.019	0.187	0.00

a: χ^2: Chi-square statistics.
b: Sig.: *P*-value (accompanying probability; significance level $\alpha = 0.05$).
c: If $P > \alpha$, accept null hypothesis (H_0). It represents no significant difference.

Table 5 The nonparametric tests (2-independent samples) between the measured parameters for the studied samples.

Tests	Parameters									
	TOC%	S1	S2	HI	T_{max}	R_o%	QI	PI	BI	S1 + S2
(a) Mann–Whitney sig	0.009	0.009	0.009	0.675	0.009	0.009	−0.175	0.046	0.047	0.009
(b) Moses Test	0	0	0	0.976	0	0	0.738	0.5	0	0
(C) Kolmogorov–smirnovz	0.013	0.013	0.013	0.815	0.013	0.013	0.329	0.082	0.082	0.013

Table 6 Pearson's correlation coefficient (r) between assessed parameters of petroleum potential of organic materials.

Parameters	TOC%	S1	S2	HI	OI	T_{max}	R_o%	QI	PI	BI	S1 + S2
TOC%	1										
S1	0.748	1									
S2	0.884	0.907	1								
HI	−0.226	0.363	0.205	1							
OI	0.676	0.476	0.674	0.045	1						
T_{max}	0.776	0.833	0.824	0.029	0.49	1					
R_o%	0.811	0.717	0.806	−0.161	0.437	0.701	1				
QI	−0.144	0.448	0.292	0.922	−0.074	0.142	−0.038	1			
PI	0.577	0.76	0.647	0.232	0.309	0.77	0.434	0.354	1		
BI	0.025	0.622	0.387	0.836	−0.037	0.27	0.109	0.932	0.525	1	
S1 + S2	0.866	0.945	0.995	0.247	0.638	0.841	0.799	0.335	0.686	0.45	1

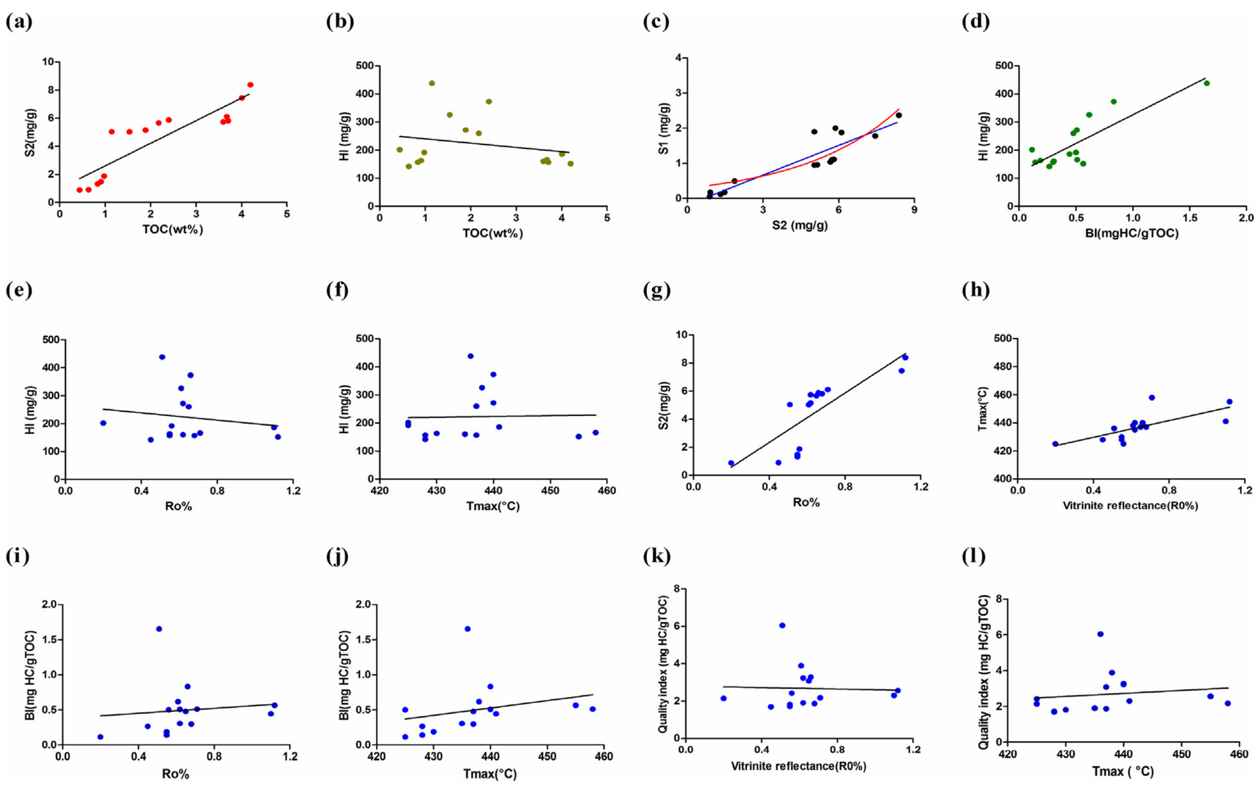

Figure 6 Pearson's correlation coefficient and linear regression between the measured parameters and thermal maturity (R_o% and T_{max})

the S2 is contributed from TOC. A clear correlation was observed between TOC and S1, QI, T_{max}, R_o, PI and S1 + S2 (Table 6) whereas, the plotting of HI vs. TOC showed no significant trend (Fig. 6b). Furthermore, two different trends were observed in the cross plot of S1 vs. S2 (Fig. 6c) which might be attributed to the compositional difference in organic material. Both BI (Bitumen index) and HI were shown to be strongly correlated (Fig. 6d). However, no significant correlation was observed between HI, R_o% and T_{max} (Fig. 6e and f, Table 6) indicating that the highest HI occurs at certain maturities (R_o% and T_{max}) and doesn't occur in stages of less maturity or over maturity. A positive correlation was observed between R_o% and S2 (Fig. 6g, Table 6) indicating that the S2 values increase with upgrading of the maturity. Additionally, T_{max} and R_o% were found to be positively correlated which confirms that both Rock–Eval pyrolysis and vitrinite reflectance can be used as indicators of thermal maturity (Fig. 6h). No significant correlation was observed between R_o, T_{max} and BI or QI (Fig. 6i–l, Table 6). The values of BI and QI showed an increase in their values at the early stage of maturity and then gradually declined with increasing maturity.

4. Conclusions

Rock–Eval pyrolysis and multivariate statistical analysis are discussed to investigate the level and time of hydrocarbon generation and expulsion of shale successions in Safir oilfield, they showed that:

(1) The Bahariya Formation is considered a poor source rock for oil generation and has a lesser degree of thermal

maturation. The shale rocks of Alam El-Bueib and Khatatba Formations are good and an excellent source rock potential for oil generation.

(2) Cluster analysis classified the source rocks into two types: Cluster I represents Alam El Bueib source rock with HI ranging between 260 and 438 mgHC/gTOC. Cluster II was divided into two subgroups IIa and IIb. Cluster IIa represents Bahariya source rocks with HI values of 142–202 mgHC/gTOC. Cluster IIb represents Khatatba source rocks with HI values of 152–186 mgHC/gTOC.

(3) Factor analysis showed that there are two factors affecting the source rock evaluation potentiality in the study area. Factor 1 includes (TOC, S1 and S2) which determine the quantity of the organic matter and (R_o%, T_{max} and PI) which determine the thermal maturity of the organic matter. Factor 2 includes (HI, QI and BI) which determine the quality of the organic matter.

(4) The PI and BI, the nonparametric tests (*K*-independent samples) between the dataset of the rock samples confirmed that the distribution of the values from respective parameters exhibits significant difference ($P < 0.05$) while, nonparametric tests (2-independent samples) showed that there was no significant difference ($P > 0.05$) in the distribution of HI and QI values.

(5) Pearson's and linear regression analysis indicated a positive correlation between TOC and S2. A strong correlation between TOC and S1, QI, T_{max}, R_o%, PI and S1 + S2. No significant trend was obtained between HI and TOC. Furthermore, two different trends were observed in the cross plot of S1 vs. S2 which might be attributed to the compositional difference in organic material. A significant correlation was between BI and QI, no correlation between HI and thermal maturity (R_o% and T_{max}) exploring that the highest HI occurs at certain maturities and doesn't occur in stages of less maturity or over maturity. Moreover, a positive linear correlation was observed between R_o% and S2 indicating elevated S2 values with increasing maturity. A positive linear correlation between T_{max} and R_o% confirms that both Rock–Eval pyrolysis and vitrinite reflectance can be used as indicators of thermal maturity. No significant correlation was observed between BI, QI and thermal maturity (R_o% and T_{max}).

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